Spin Measurements through Quantum Interference

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Outline

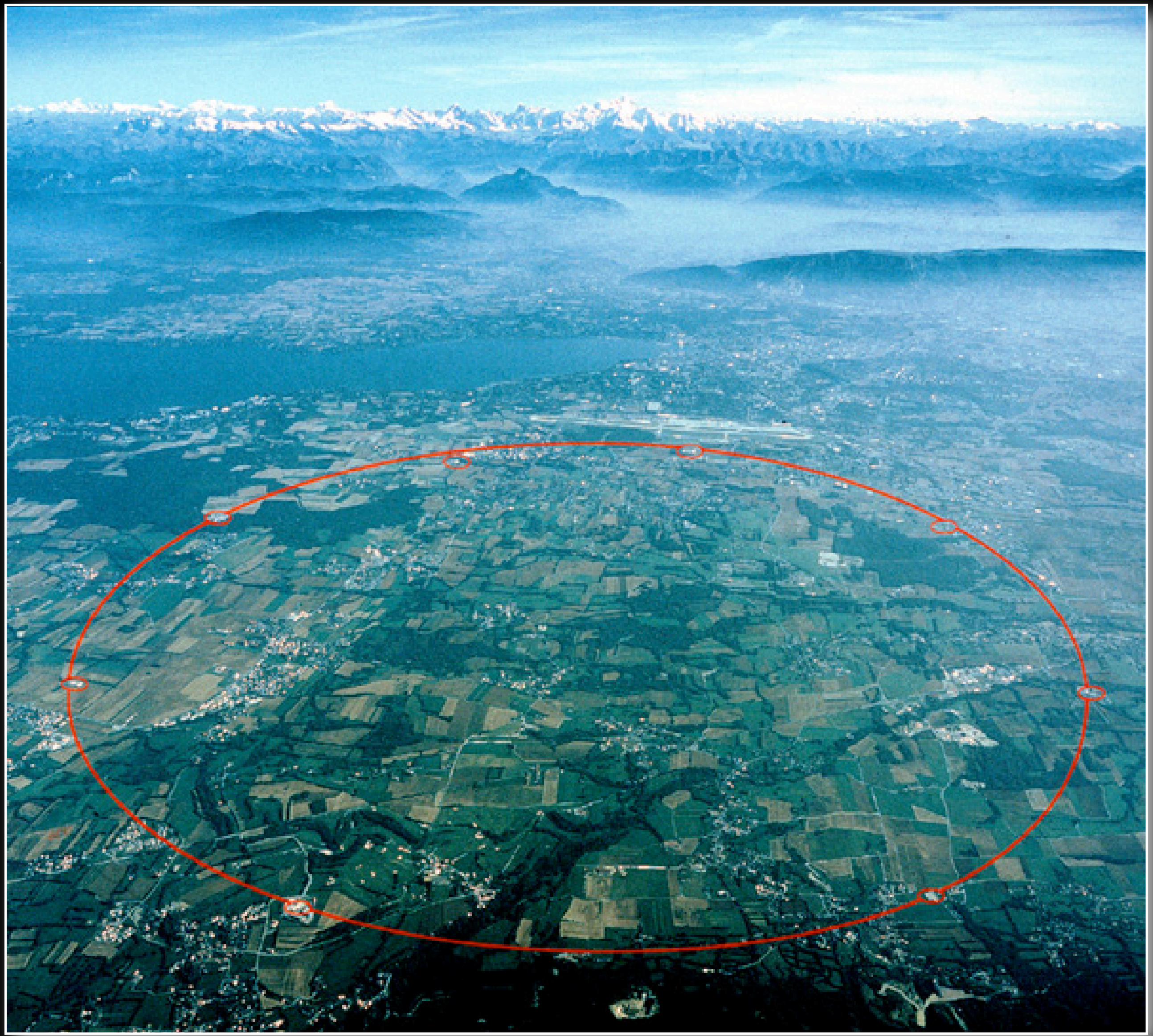
- Motivation
- Interference of Helicity States
- SM Applications at Tevatron
- Extension to the LHC
- Conclusion

The LHC Era

- Finally have access to TeV-scale physics
  - Solution to the Hierarchy Problem?
  - Dark Matter?

$\Longrightarrow$ New Particles

  - SUSY, Extra-Dimensions, Little Higgs? Something totally different?



SUSY vs. UED

- Very similar experimental signatures
  - 'Copies' of the Standard Model

$$\begin{aligned} W^{\pm}, Z, A &\rightarrow \tilde{W}^{\pm}, \tilde{Z}, \tilde{A}\ (\tilde{\chi}_i^{\pm}, \tilde{\chi}_i^{0}) \\ &\rightarrow W_1^{\pm}, Z_1, A_1, W_2^{\pm}, Z_2, A_2, \ldots \end{aligned}$$

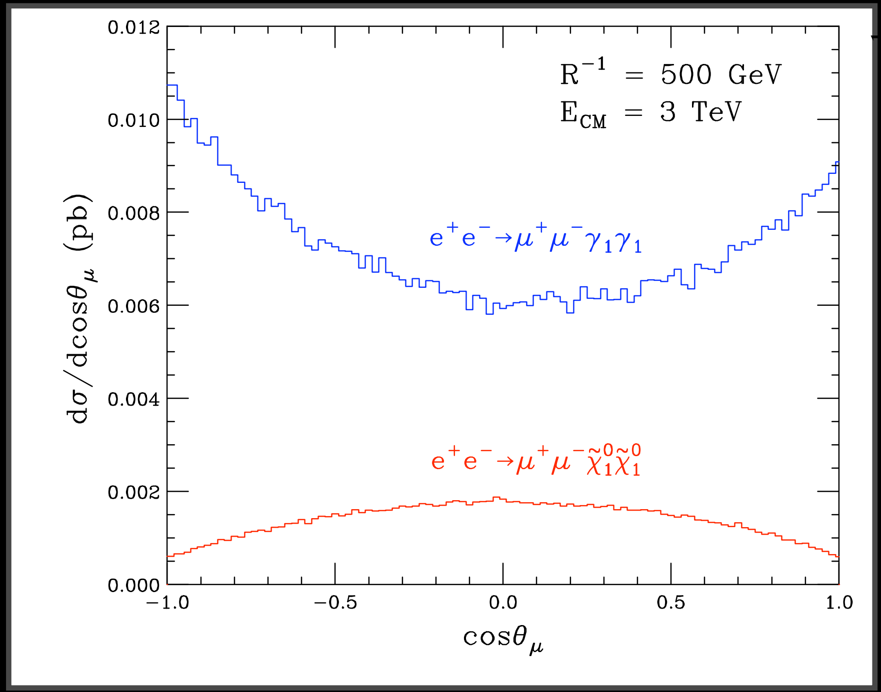
  - Dark Matter candidate $\rightarrow$ large $\not{p}$
- Spin measurements may be the defining experimental test.

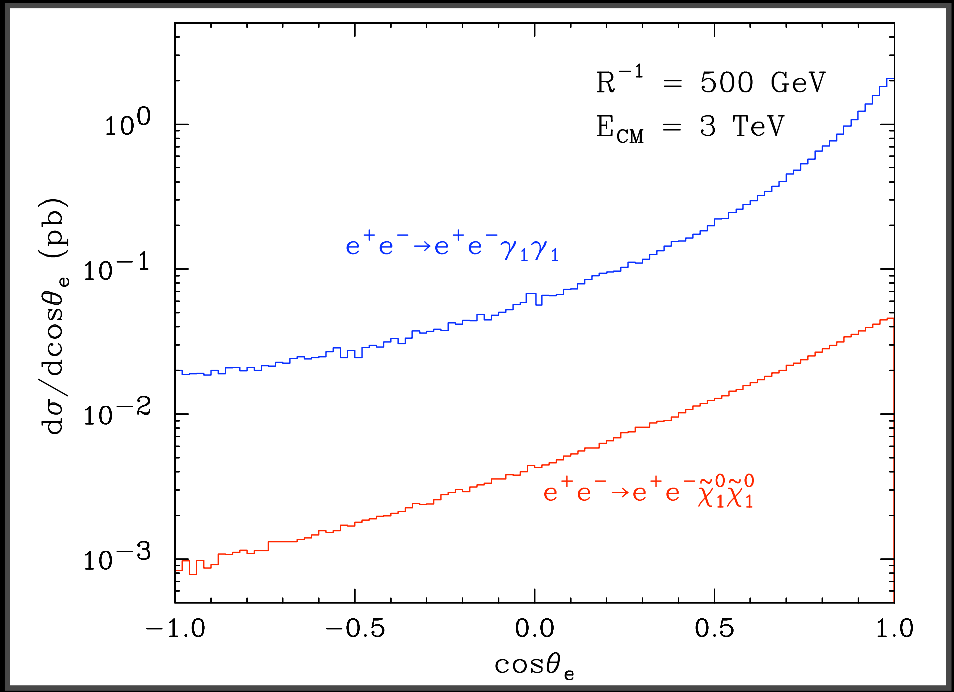
Spin Measurements

- Most techniques for next-generation colliders concentrate on distinguishing models:
  - Comparison of total cross section
    $$\sigma_{SUSY} < \sigma_{UED}$$
  - Look for higher KK modes in UED
- At a linear collider can use threshold scans:
  - Scalar $\sigma \propto \beta^3$, spinor/vector $\sigma \propto \beta$
  - Cannot distinguish higher spin modes

Spin Measurements

- At ILC: reconstruct production angle



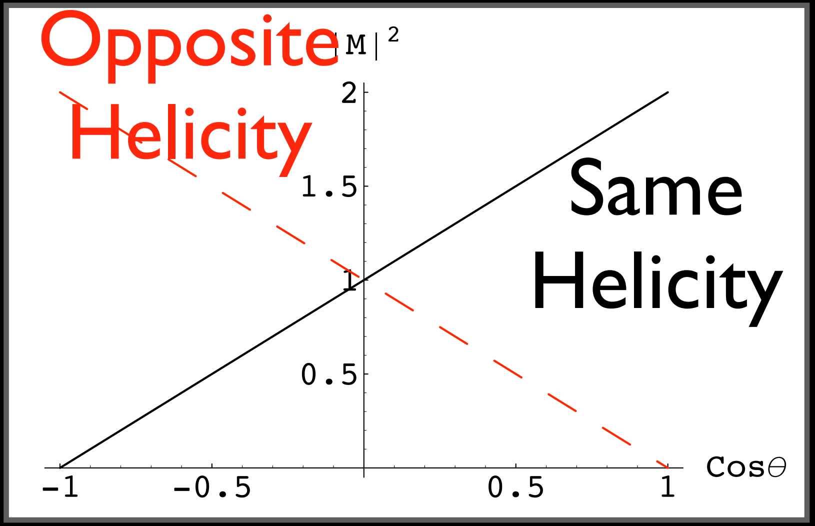


- t-channel introduces model dependence: forward peak

Spin Measurements

- Spin dependence of decay angles:

Decay of polarized spinor
to spinor/scalar →



Assumes chiral couplings

- Using long decay chain at LHC can distinguish spinors from phase space:

Near Far

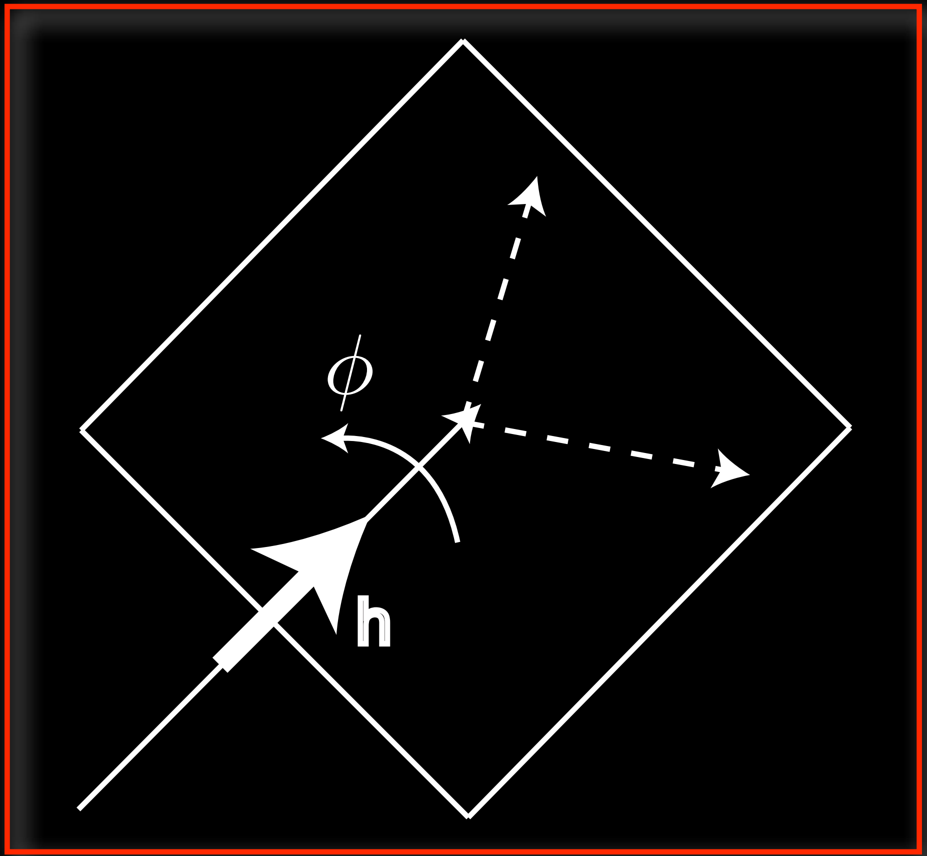
$$\tilde{q}_L \longrightarrow \tilde{\chi}_2^0 q_L \longrightarrow \tilde{\ell}_R^{\pm} \ell^{\mp} q_L \longrightarrow \ell^{\pm} \ell^{\mp} q_L \tilde{\chi}_1^0$$

  - Polluted with near/far ambiguity, anti-squark production, and assumes chiral coupling

Spin and Quantum Interference

- Want a spin measurement with as few assumptions as possible.
- Back to Quantum Mechanics!
- Decay of particle with helicity h
  - Rotations about the z-axis (particle momentum) implies that

$$\mathcal{M}_{\text{decay}} \propto e^{iJ_z\phi} = e^{ih\phi}$$



Spin and Quantum Interference

- If particle is produced in multiple helicity states and then decays, then decay amplitudes interfere coherently:

$$\boxed{\begin{gathered}\sigma \propto \left|\sum \mathcal{M}_{\mathrm{prod.}} \mathcal{M}_{\mathrm{decay}}\right|^2 \\ \mathcal{M}_{\mathrm{decay}}(h,\phi) = e^{ih\phi}\mathcal{M}_{\mathrm{decay}}(h,\phi=0)\end{gathered}}$$

- Sum runs over all helicities produced, generically $h = -s, \cdots, s$ in which case

$$\boxed{\sigma = A_0 + A_1 \cos\phi + \cdots + A_n \cos n\phi, \;\; n = 2s}$$

(with H.Murayama, W. Klemm, and B.Heinemann 0804.0476)

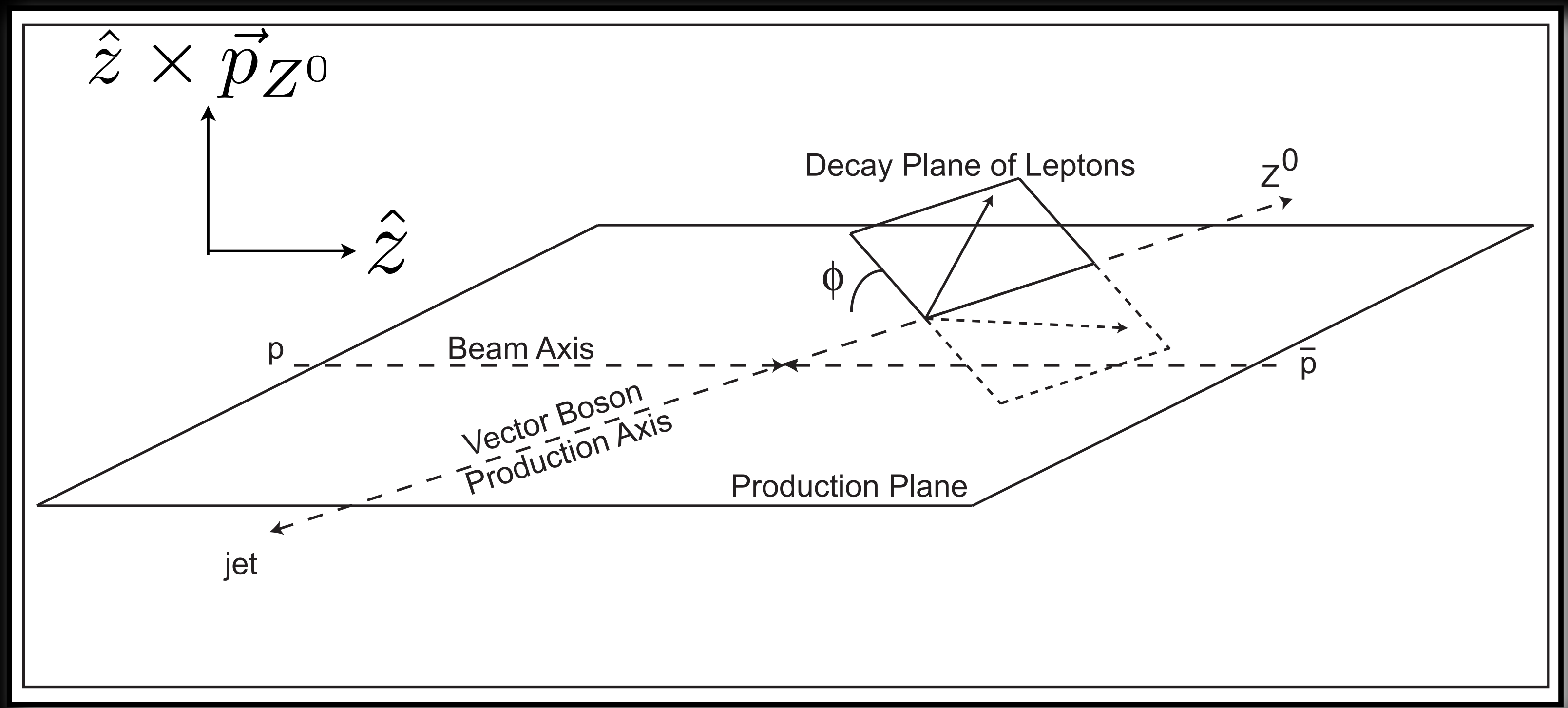
Proof of Concept

- Demonstration of technique using data already on tape, from Tevatron
  - $p\bar{p} \to Z + \mathrm{jet}, \;\; Z \to e^- e^+$
  - $\sigma = 7 \text{ pb}$ with
    $p_{T\mathrm{jet}} > 30 \text{ GeV}, \;\; |\eta_{\mathrm{jet}}| < 2.1$
    and cuts on lepton $p_T, \;\; \eta$
  - $1.7(8.0) \text{ fb}^{-1}$ total luminosity

Expect non-zero

$$A_0, A_1, A_2$$

Kinematics

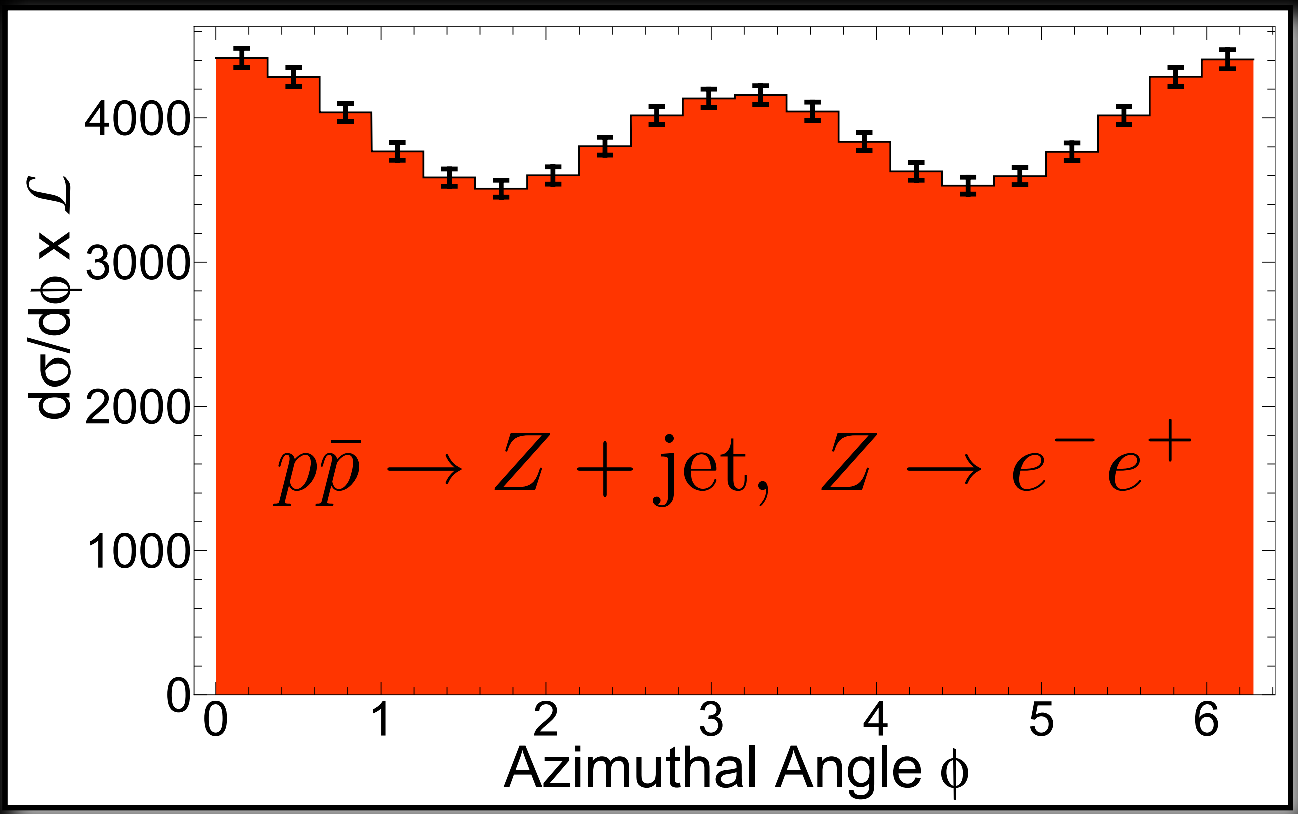


$$\cos\phi = \frac{\hat{z} \times \vec{p}_{Z^0}}{|\hat{z} \times \vec{p}_{Z^0}|} \times \frac{\vec{p}_{Z^0} \times \vec{p}_{e^-}}{|\vec{p}_{Z^0} \times \vec{p}_{e^-}|}$$

Define positive ϕ to be in the direction of $\hat{z} \times \vec{p}_{Z^0}$

Results

- Calculated cross sections using HELAS and the adaptive Monte-Carlo program BASES.
- With only cuts on jet $p_T, \ \eta$ for Tevatron data:

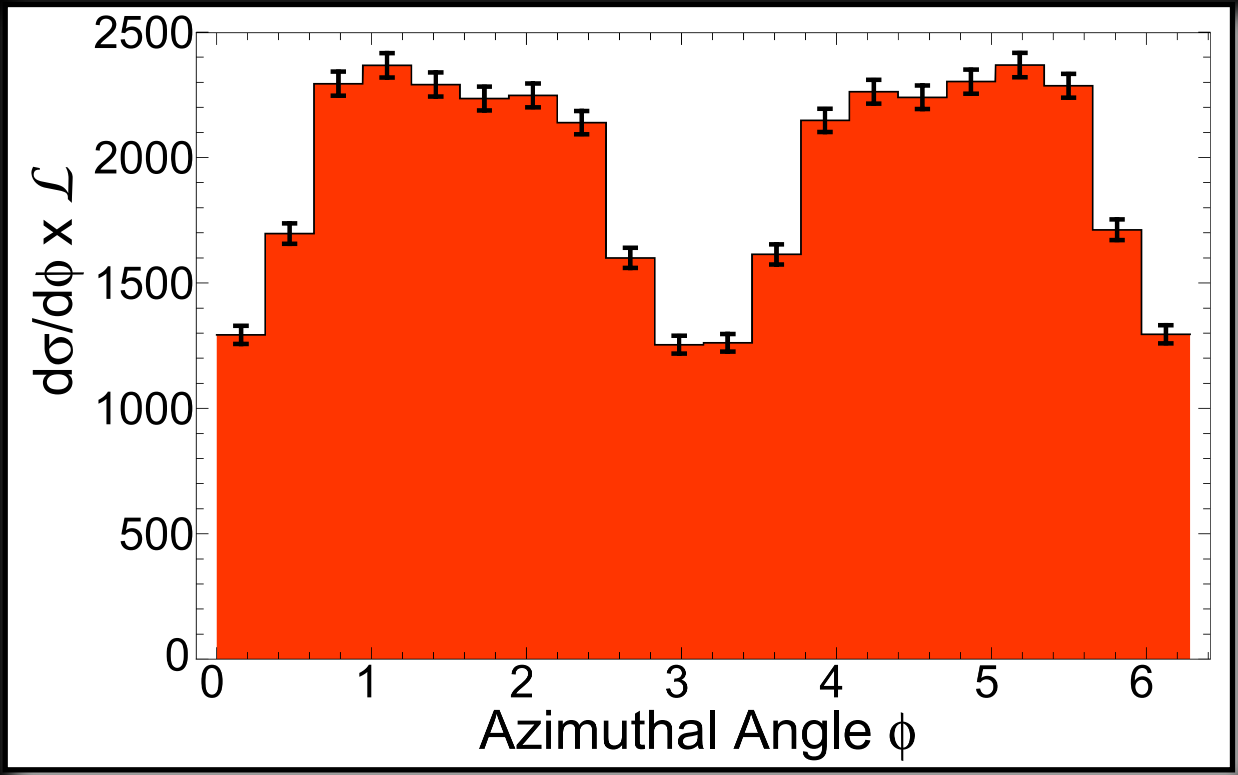


Effects of Cuts

- However, detectors cannot see forward regions, and need isolation cuts on jets/leptons.

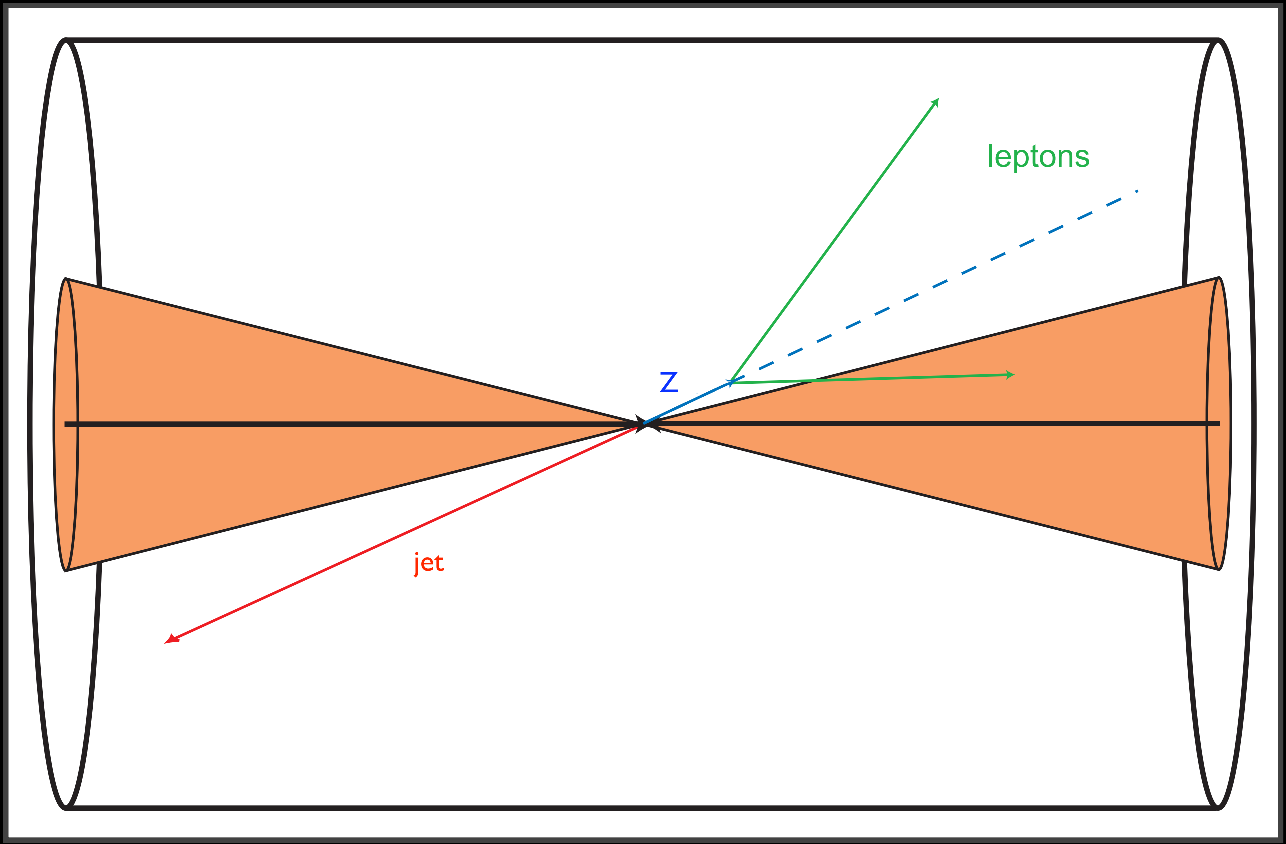
CDF cuts:

Jet transverse momentum	$p_{T,j} > 30$ GeV
Jet η	$\lvert\eta\rvert < 2.1$
Invariant mass of lepton pair	$66 < m_{\ell\ell} < 116$
Central electron η	$\lvert\eta\rvert < 1$
Second electron η	$\lvert\eta\rvert < 1$ or $1.2 < \lvert\eta\rvert < 2.8$
Electron E_T	$E_T > 25$ GeV
Electron isolation cuts	$\Delta R_{e-j} > 0.7$



Rotational Invariance

- Cuts introduce new directional dependences.
- Remove them by requiring events to pass cuts after rotation about boson axis



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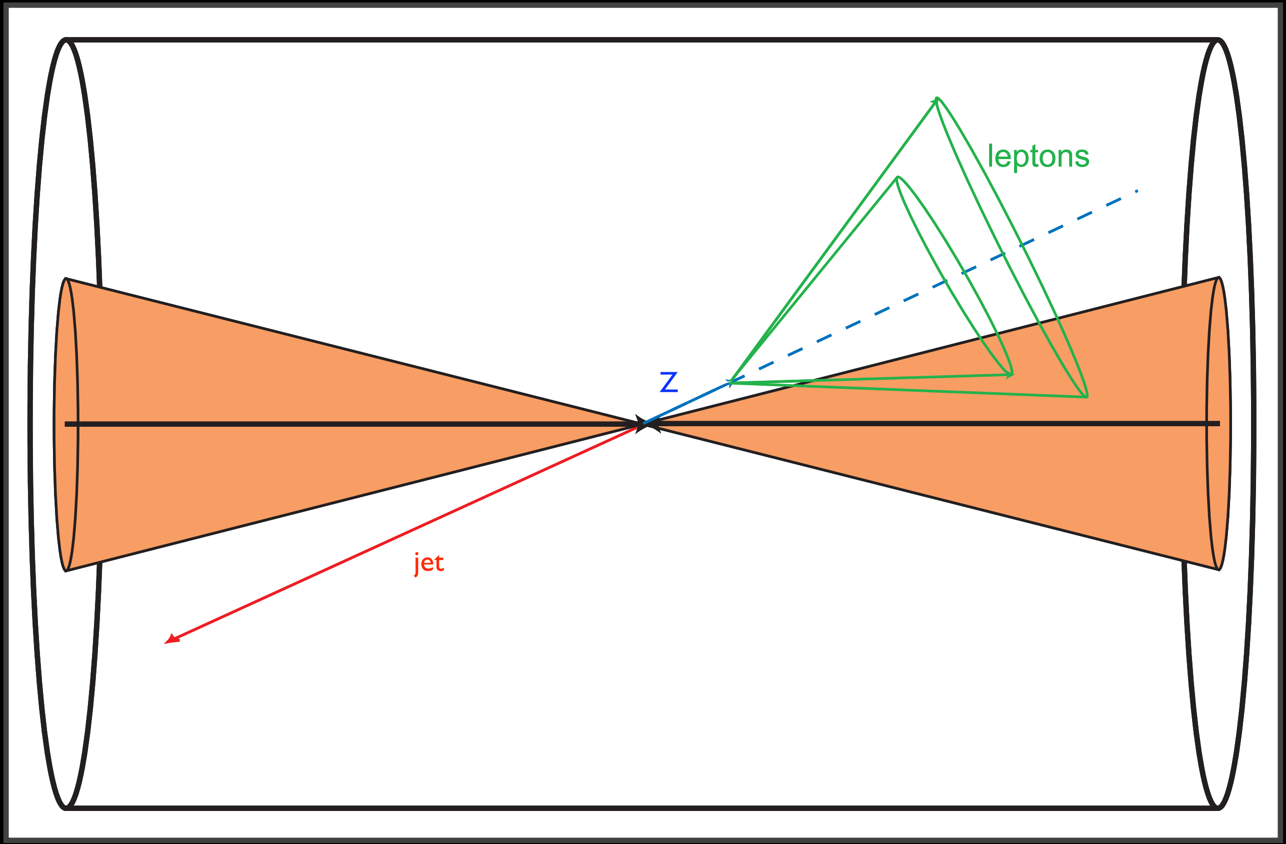
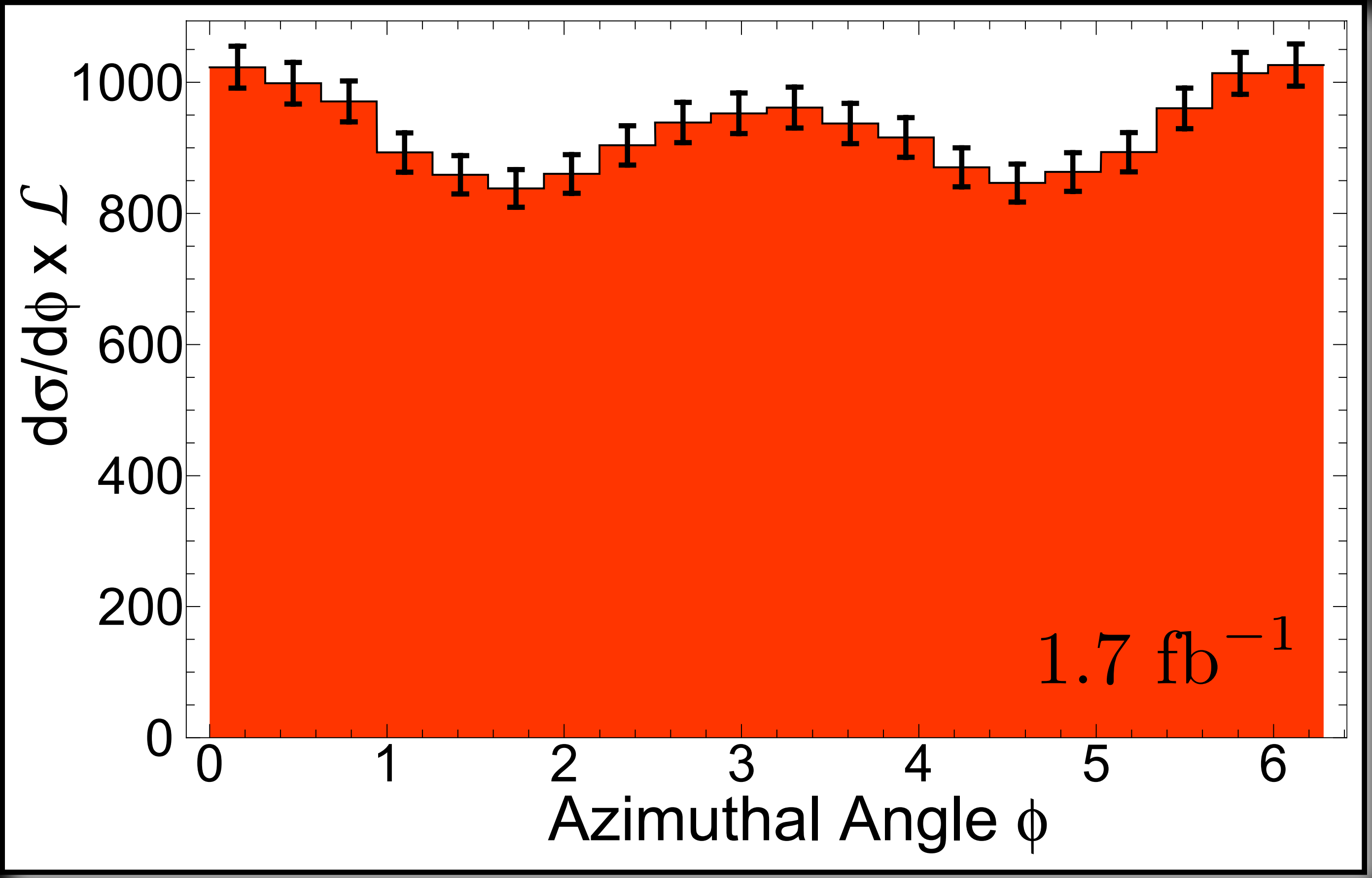


Rotationally Invariant Cuts

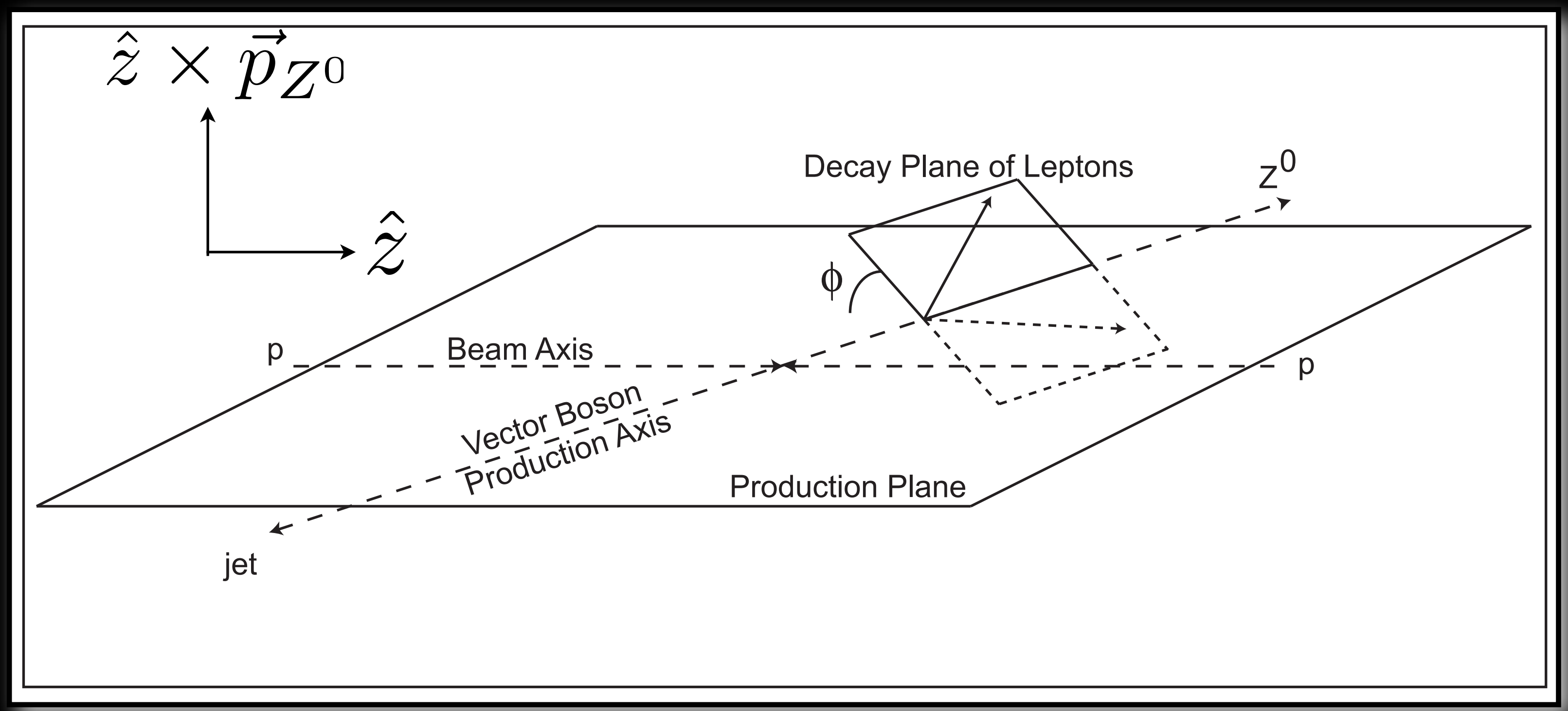
- Applying these rotationally invariant cuts
  - (And with looser acceptances on p_T, η)

A_1/A_0	0.040 ± 0.023
A_2/A_0	0.082 ± 0.023
A_3/A_0	0.000 ± 0.023
A_4/A_0	0.000 ± 0.024



Application to the LHC

- Identical beams means sign ambiguities



- $\phi \to \phi + \pi$ under this redefinition, so cannot measure odd modes from ϕ distribution

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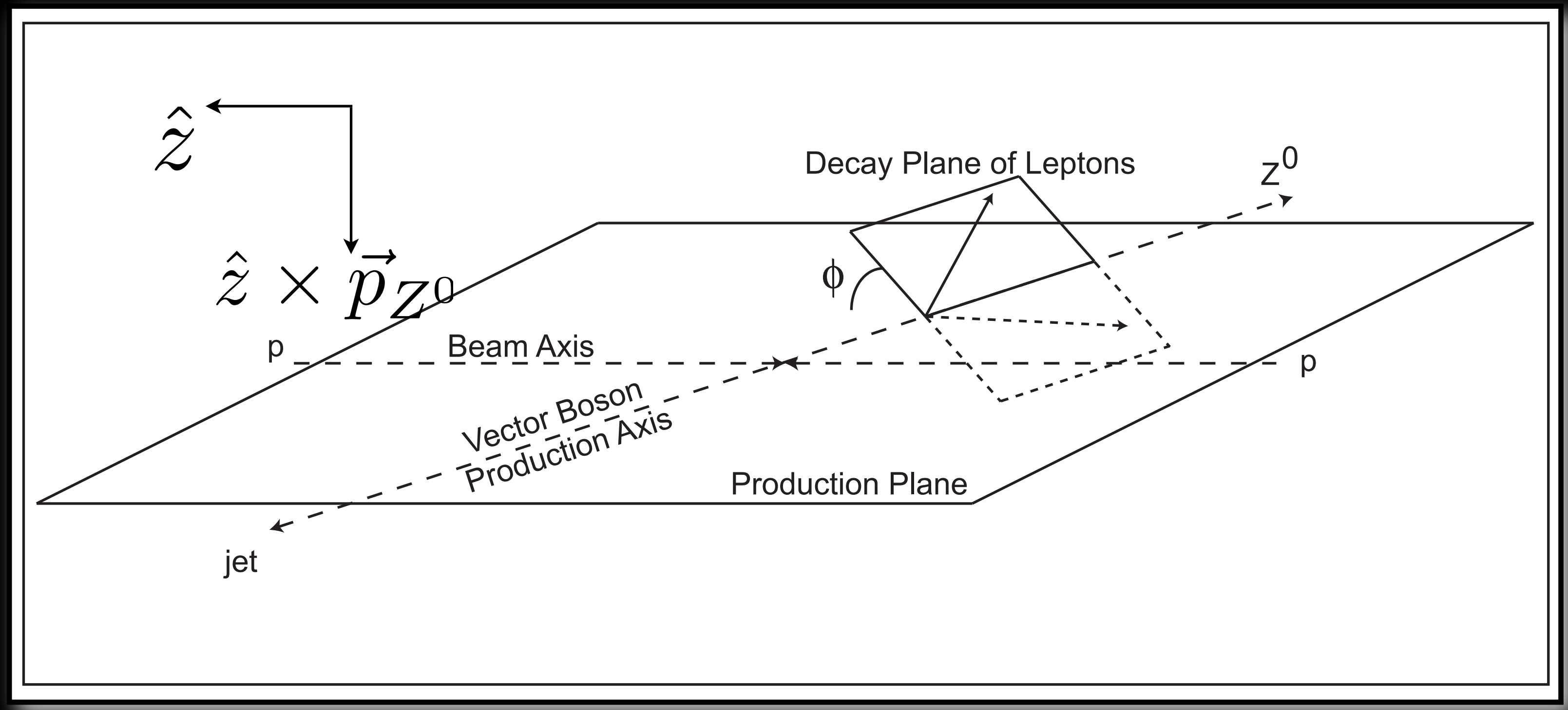

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Identical Beams

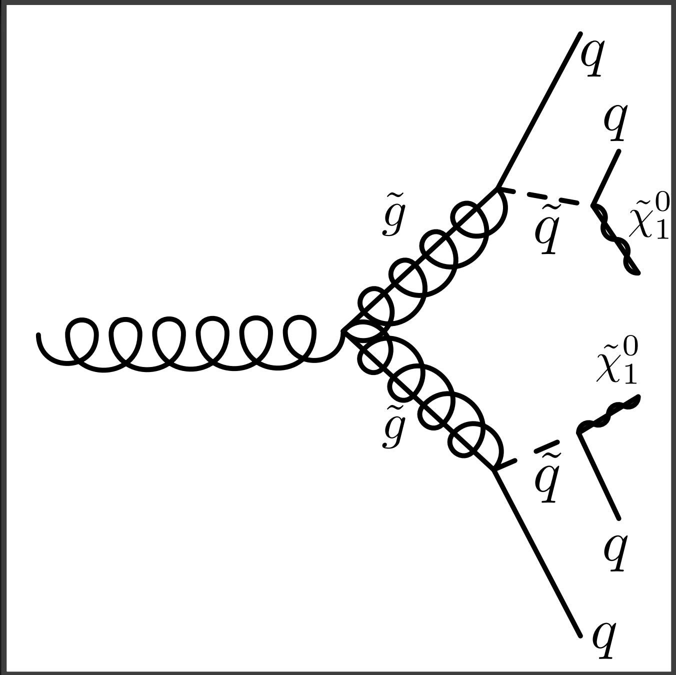
- Consider $Z + \mathrm{jet}$ at LHC. At LO, these events come from $q\bar{q}, qg, \bar{q}g$
  - If we knew which parton went with which proton, beams would no longer be identical
  - Look for situations where Z direction correlates with one of the partons. Then can pick beam closest to Z as the positive $\hat{z}$ direction
    - However, this correlation tends to be small
- For particular case of $Z + \mathrm{jet}$, $q\bar{q}$ has larger contribution to A_1/A_0 than qg, so even with 100% directional ID, $A_1/A_0 < 1\%$ at LHC

New Physics and $\not\phi$

- 'WIMP miracle' suggests new stable particles with SU(2) quantum numbers and $m \sim 100 - 1000\ \mathrm{GeV}$
  - Stability usually enforced through some new symmetry, so expect two pair-created WIMPs per event at colliders
  - Pair creation/decay of particles with *known* mass insufficient to fully reconstruct $\not\phi$ distribution

4+4 unknown momenta
-2 measured $\not p_T$
-6 mass relations

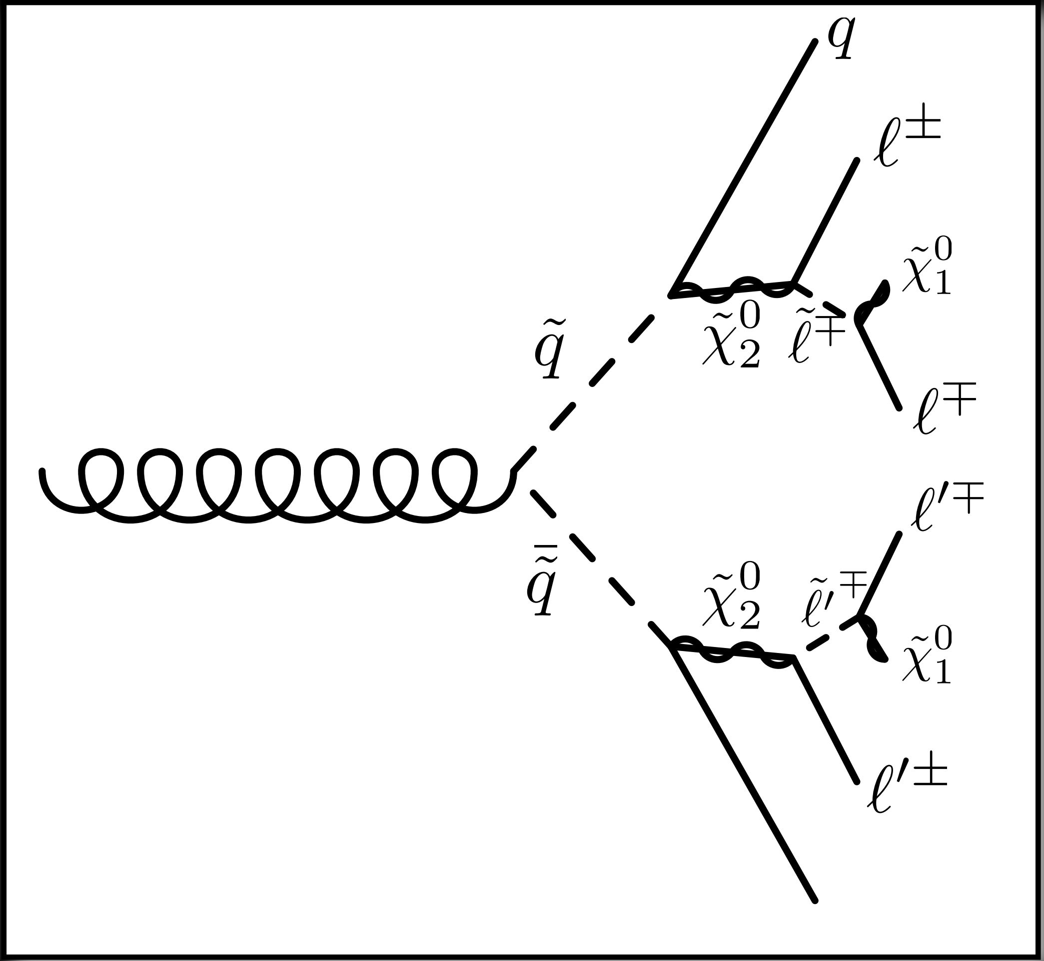
4-fold ambiguity



New Physics and $\not{p}$

- Can look at even longer decay chains
- Starts to lose model independence
- Problems with reconstruction, near/far ambiguities, need accurate mass measurements...

More work needed



Summing up

- Interference of helicity states provides a model-independent method of spin measurements.
- Method can be tested with current data on vector bosons at Tevatron
  - Data analysis currently being performed
  - Tevatron presents certain advantages over LHC in searching for odd modes
  - Differences in $p/\bar{p}$ p.d.f.s can give drastically different signals at Tevatron vs. LHC